Beyond The Standard Model

A lightning introduction

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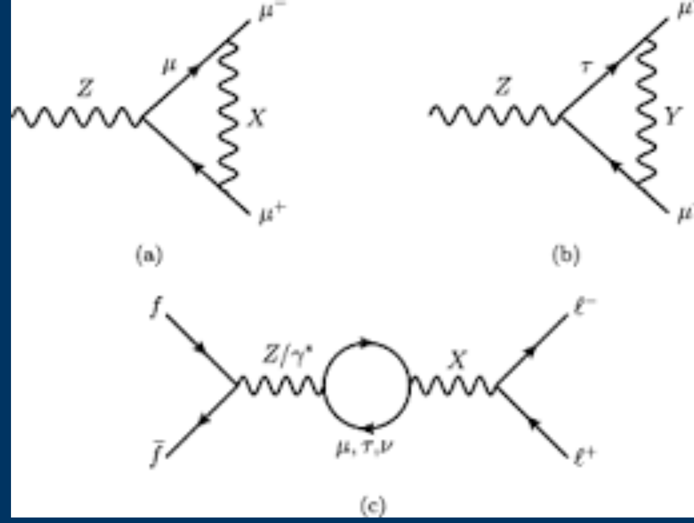
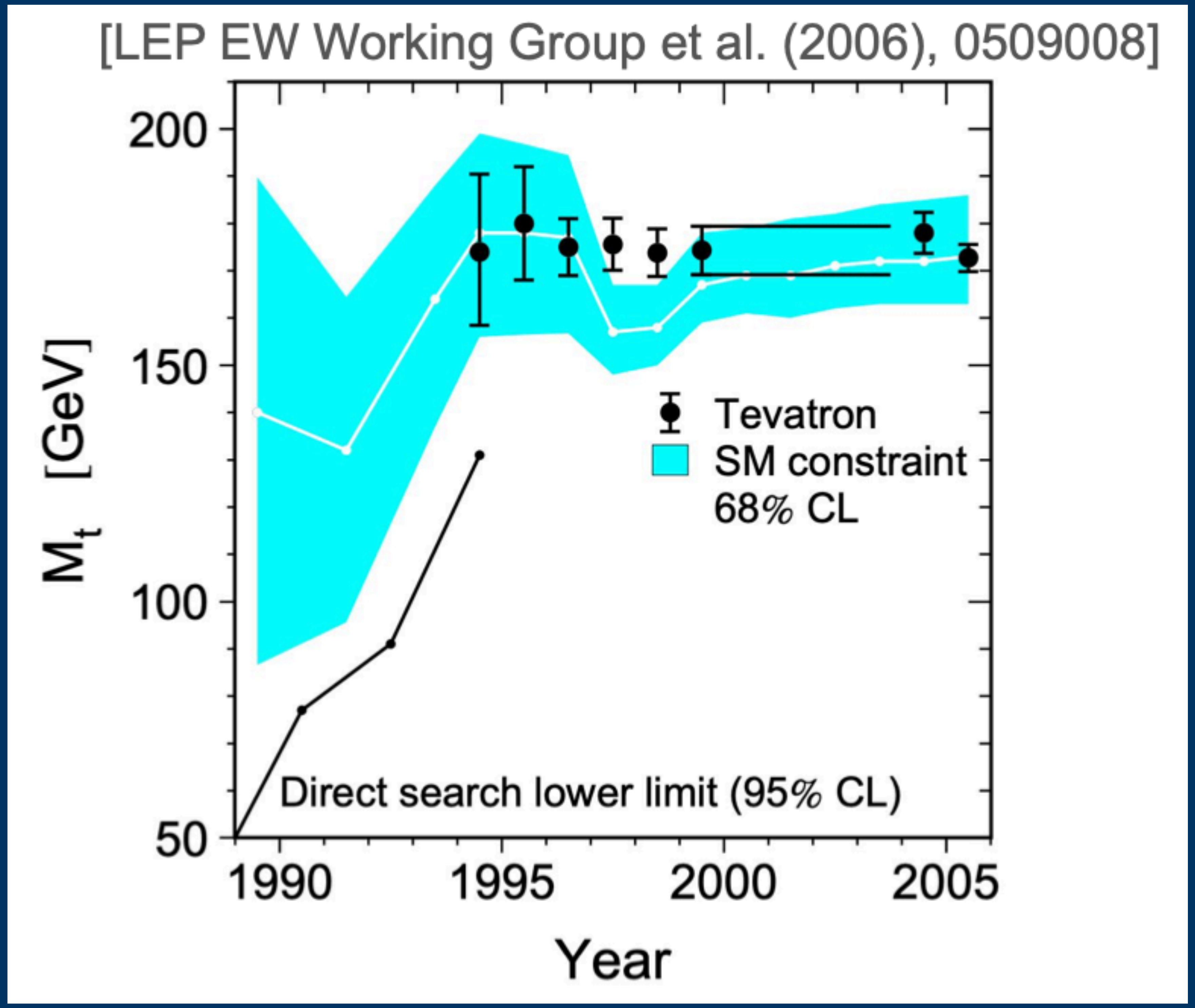
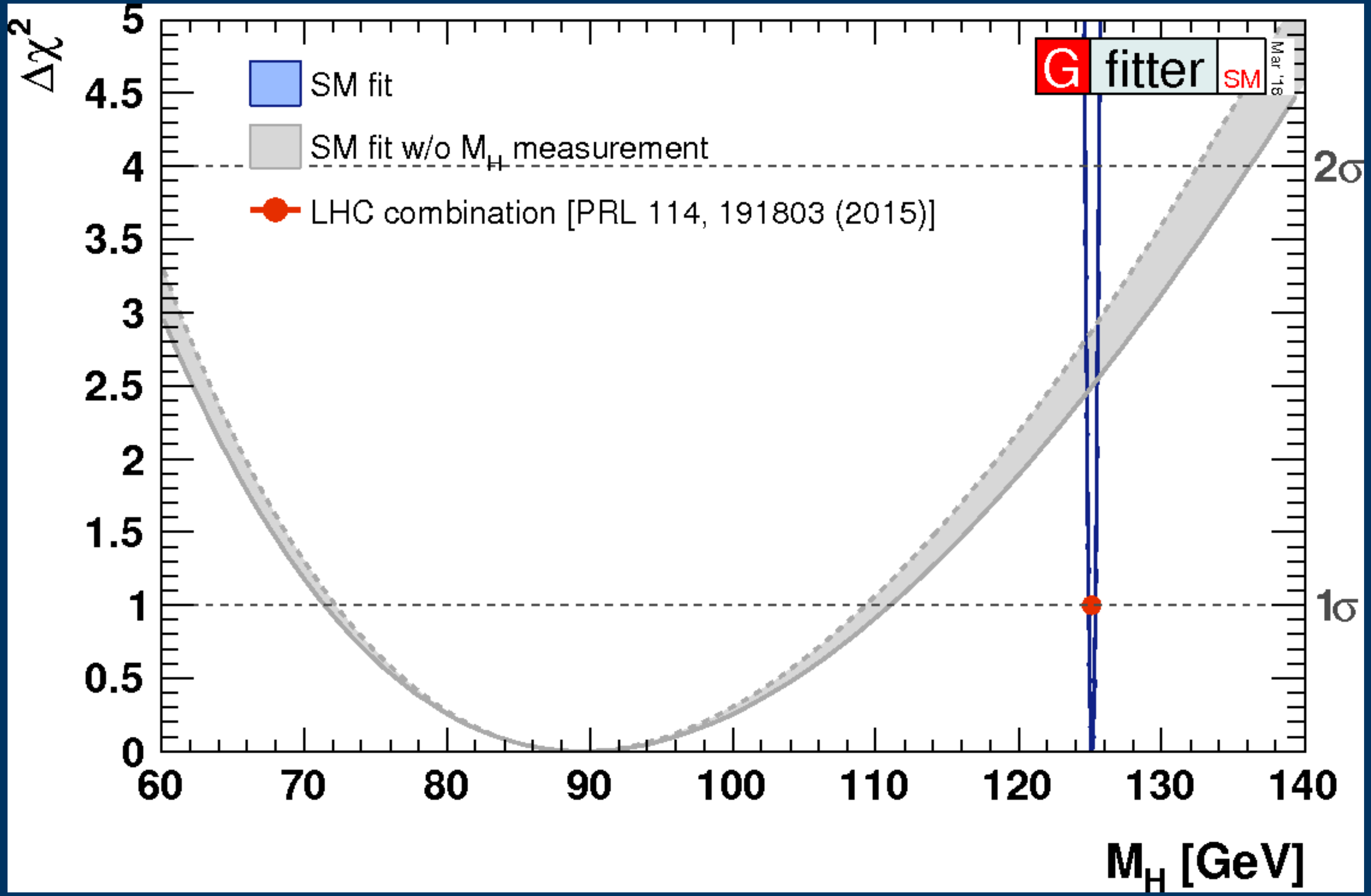
SM has been extremely successful in all tests, up to now!



- Being a renormalizable theory the SM can be subject to very stringent tests
- EWPO agrees with direct observations
- It is unlikely the SM is the final theory!

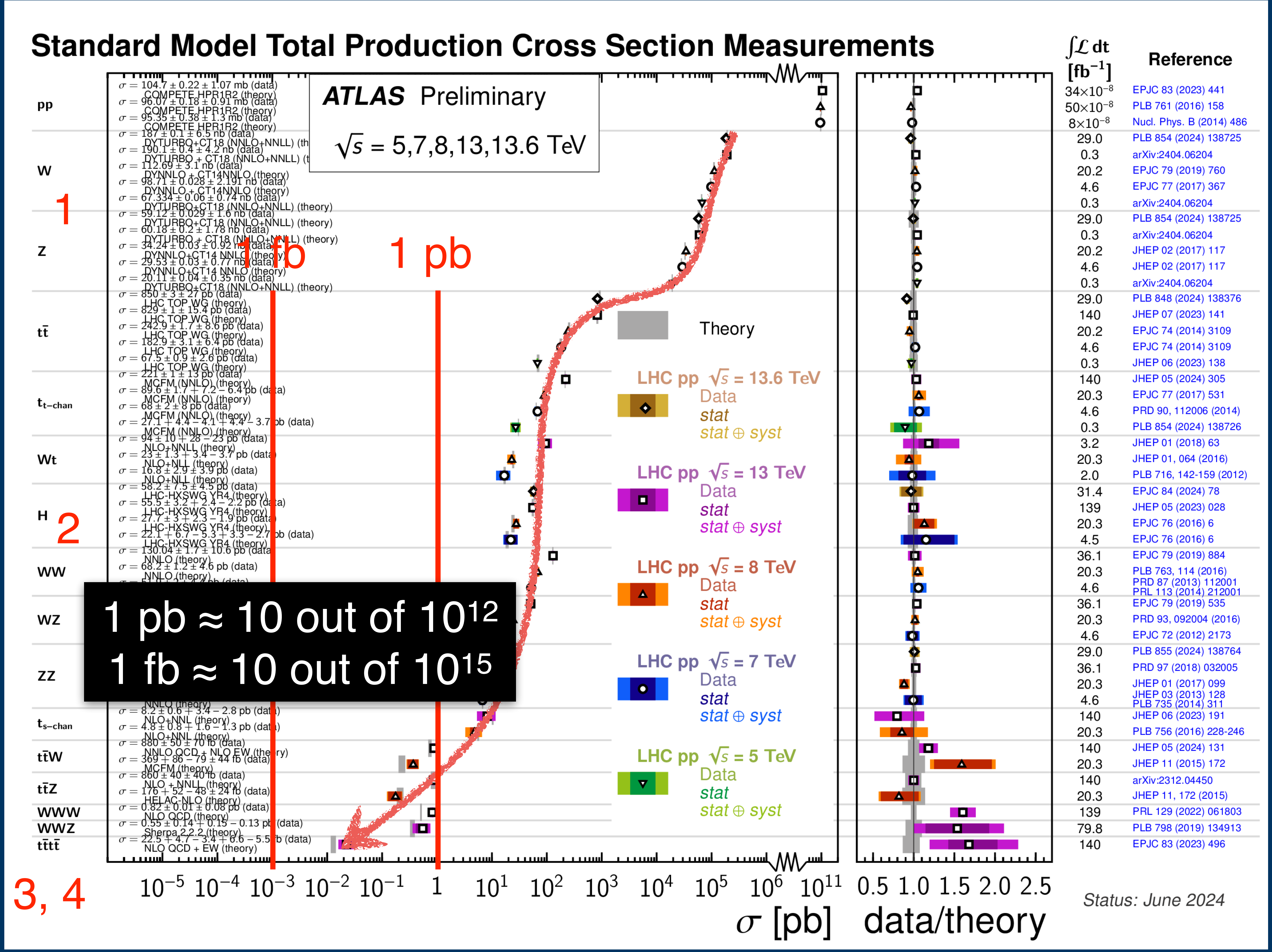




- Many SM processes have been studied
- σ varies but 10 orders of magnitude
- strong and weak processes
- In general, good agreement with SM

More multiplicity

More interesting vertices



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Smaller cross section

More rare

SM shortcomings

SM shortcomings: number of parameters

- Number of parameters:

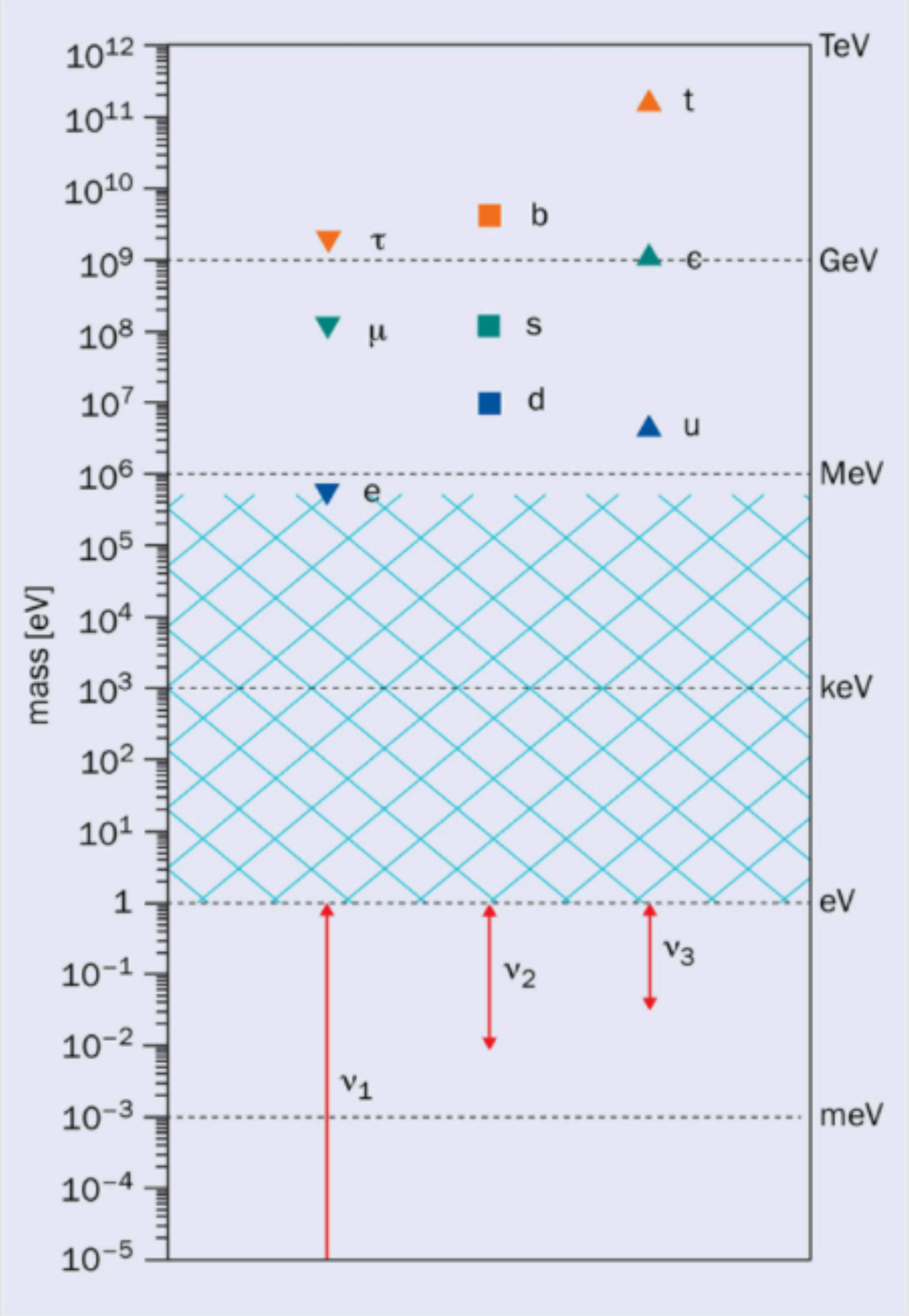
    - EW gauge sector: $g \, , \, g'$
    - QCD: $g_s \, , \, \theta$
    - SSB sector: $\lambda \, , \, v$
    - Fermion masses: $9 \times m_f$
    - CKM: $\theta_{12} \, , \, \theta_{13} \, , \, \theta_{23} \, , \, \delta$
    - Total: 19 independent parameters

- For massive neutrinos add 3+4 (Dirac) ou 3+6 (Majorana)!
- There are too many parameters to be a final theory!

SM shortcomings: spectrum

- Large range of the SM particle masses!
- There is no explanation for $\frac{m_e}{m_t} \simeq 3 \times 10^{-5}$
- It gets worse considering the neutrinos!
- In the SM translate to a wide range of Yukawa couplings

$$Y\, \bar{L} \varphi e_R$$

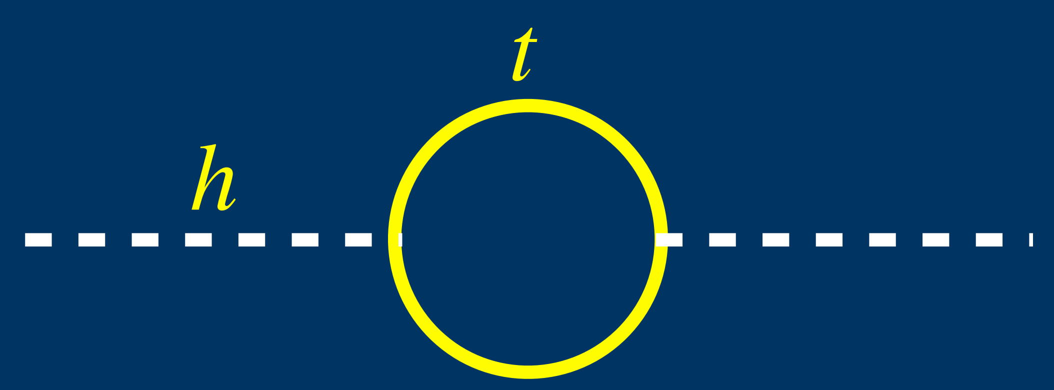


SM shortcomings: hierarchy problem

- It’s hard to understand a light scalar also known as the hierarchy problem:

$$m_h = 125.11 \text{ GeV} \ll M_{\text{Planck}} = 1/\sqrt{G_N} \simeq 1.2 \times 10^{19} \text{ GeV}$$

- quantum corrections to the Higgs mass $\Delta m_h^2 \propto \dfrac{y_t^2}{16\pi^2}\Lambda^2$

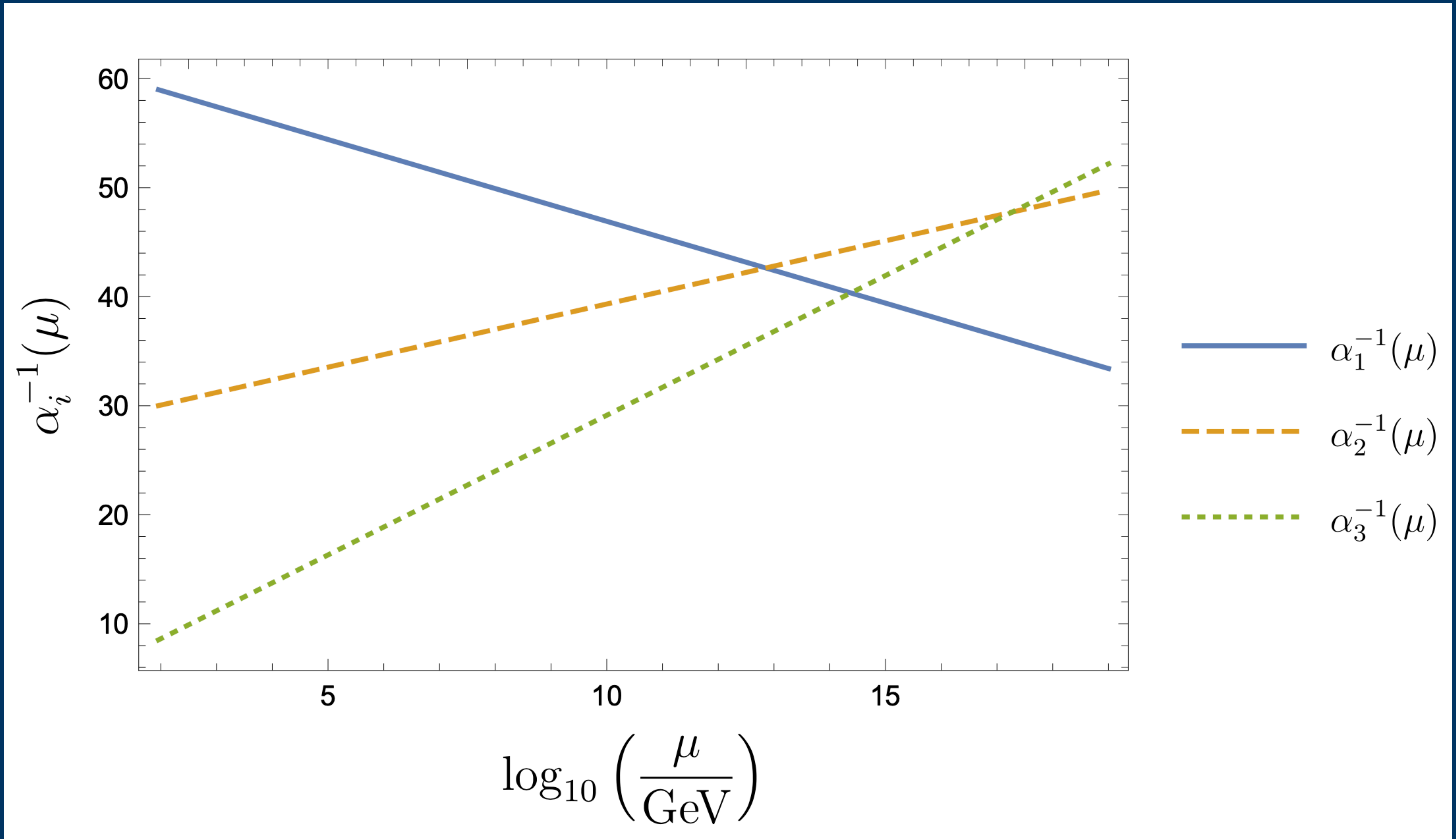


- Why the Higgs mass is not close to the large mass scale Λ?

- There is no symmetry protecting the scalar (Higgs) mass in the SM.

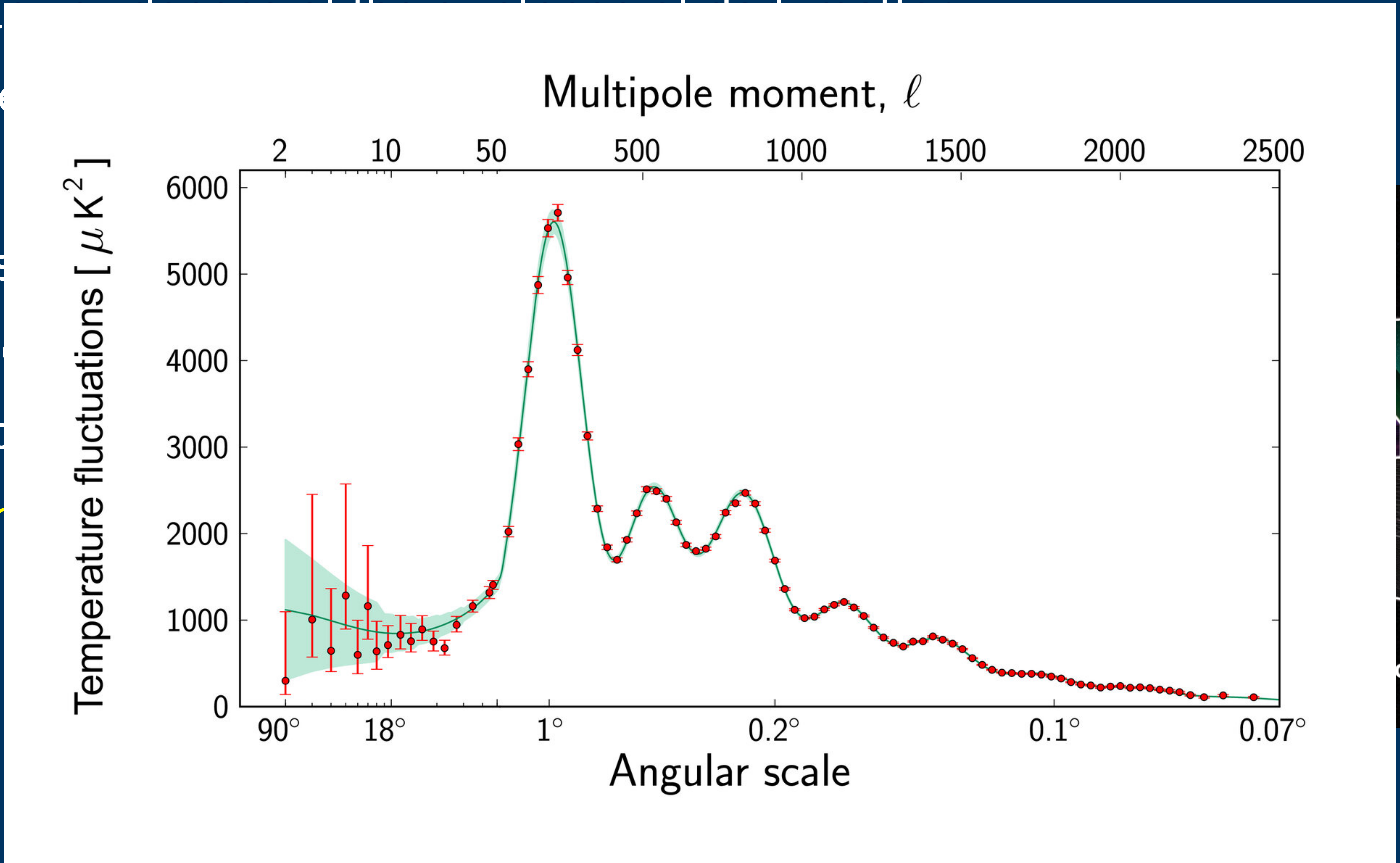
SM shortcomings: unification

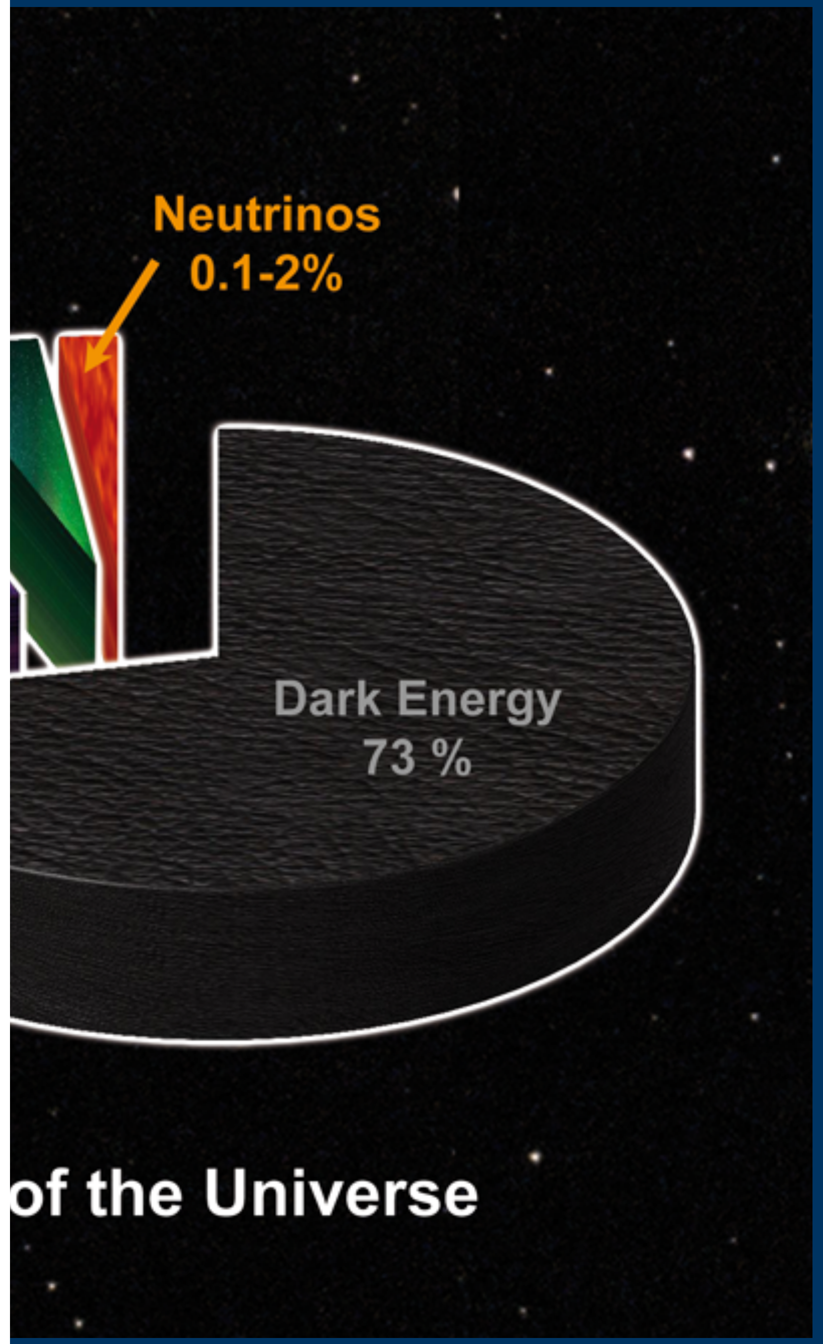
- We know force unifications: electricity and magnetism; weak and electromagnetic forces
- The couplings constants to not unify in the SM



SM shortcomings: dark matter

- There are ma
- Galaxy (cluste
- Gravitational
- CMB power s
- Fit to cosmolo
- 23% of the to
- The SM has n





SM shortcomings: matter-antimatter asymmetry and CP

- Conditions to generate the matter-antimatter asymmetry:

    1. Departure from thermal equilibrium
    2. Baryon number violation
    3. CP violation

- In the case of the SM:

    1. EW phase transition is a smooth cross over
    2. Baryon number violation is achieved via sphelarons
    3. CP violation is not enough

- The SM has an additional problem with CP: $\theta \, \frac{g_S^2}{32\pi^2} \, \tilde{G}^a_{\mu\nu} G^{a\,\mu\nu}$ must have $\theta < 10^{-10}$

Model building recipe (2000's)

- Given a SM shortcoming that you want to solve:

  1. Choose the spacetime geometry!
  2. Choose the local gauge symmetry
  3. Choose the matter content and its representation(s)
  4. Choose the symmetry breaking sector (perturbative/non-perturbative)
  5. Verify whether theoretical and experimental constraints are satisfies; if not go back to 1.

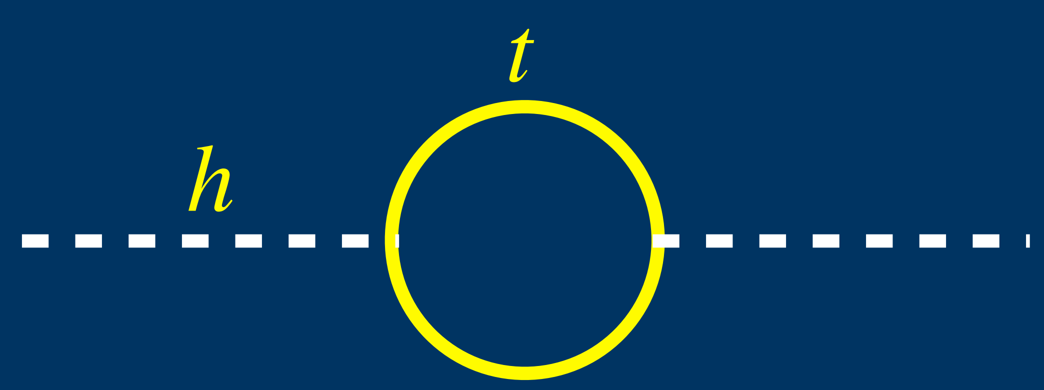
- There is a wide range of theories beyond the standard model (BSM)!


SM
anomalies
Dark matter
ν mass
matter/antimatter
CP
Hierarchy
Flavor
To be discovered
Dark energy
Unification

A FEW EXAMPLES

Supersymmetry

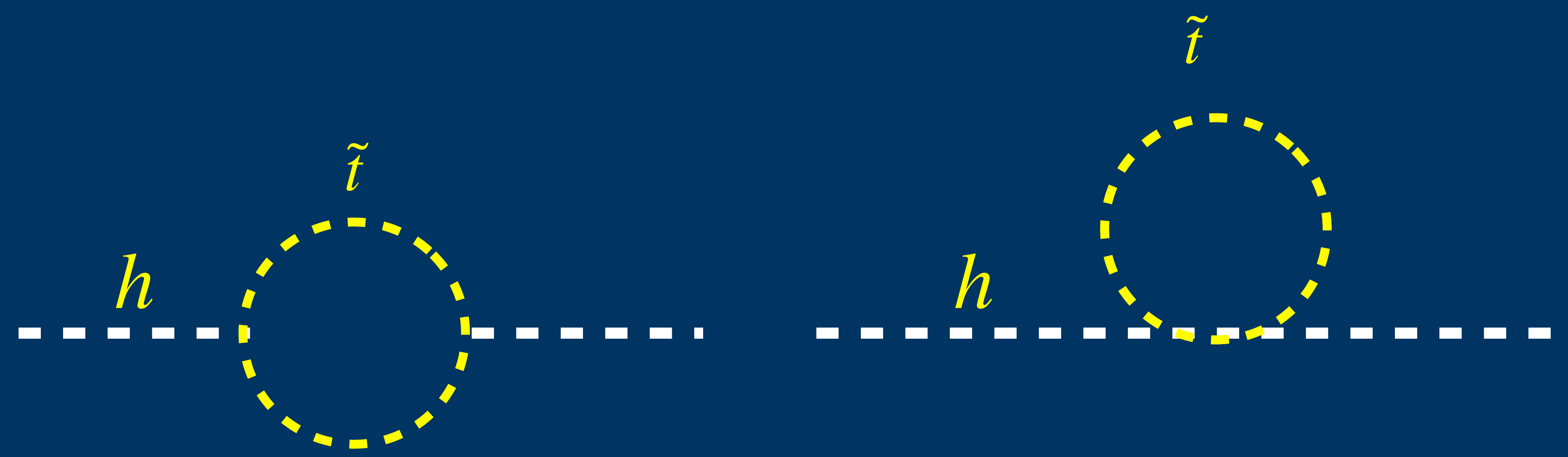
- Let's start with the hierarchy problem.
- Coleman-Mandula theorem: spacetime and internal symmetries combined in a trivial way!
- Exceptions: conformal symmetry and supersymmetry (SUSY)
- SUSY uses anticommuting generators! $\{Q, Q\} = 0$, $\{Q, Q^\dagger\} = P_\mu \sigma^\mu$, $[P^\mu, Q] = 0$
- Why? Scalar loops can cancel the effects of a fermion loop



$\tilde{t}$

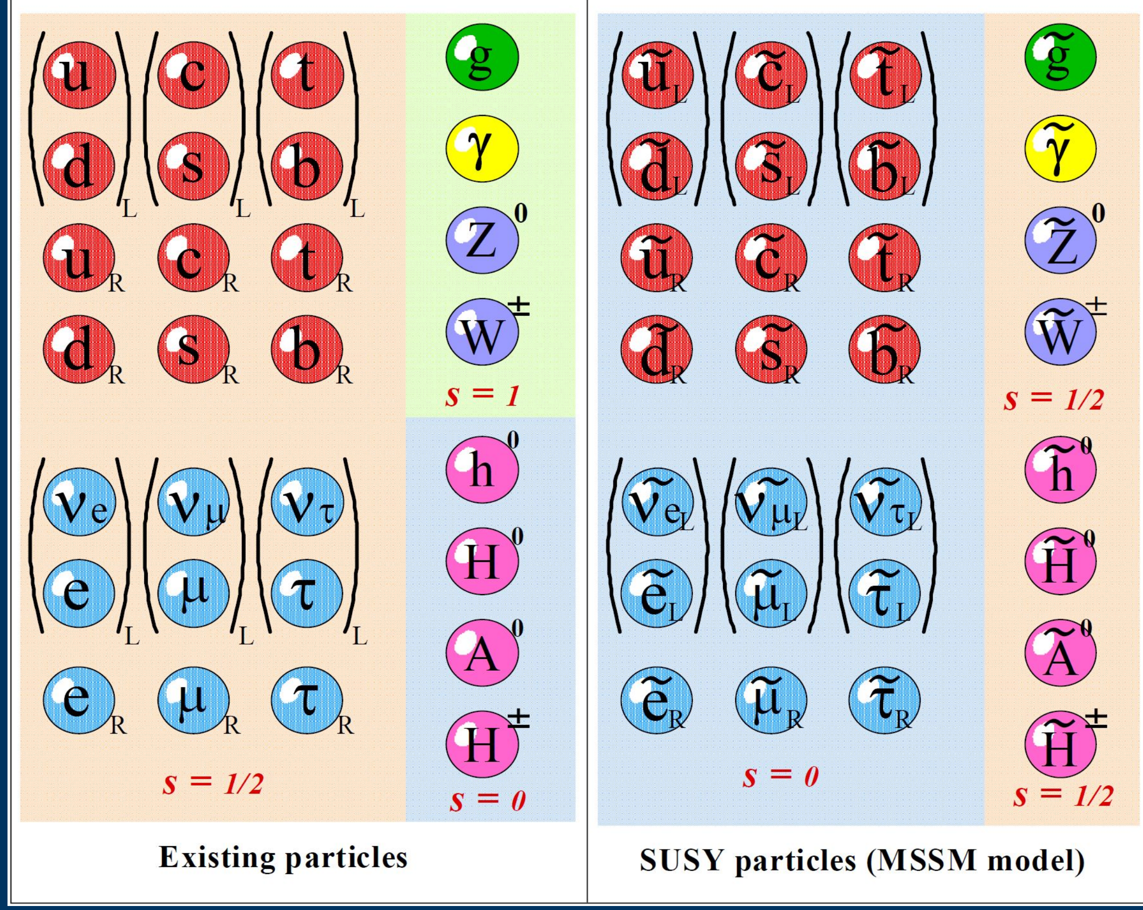
$$\Delta m_h \propto y_t^2 \Lambda^2$$

choosing c the contributions cancel

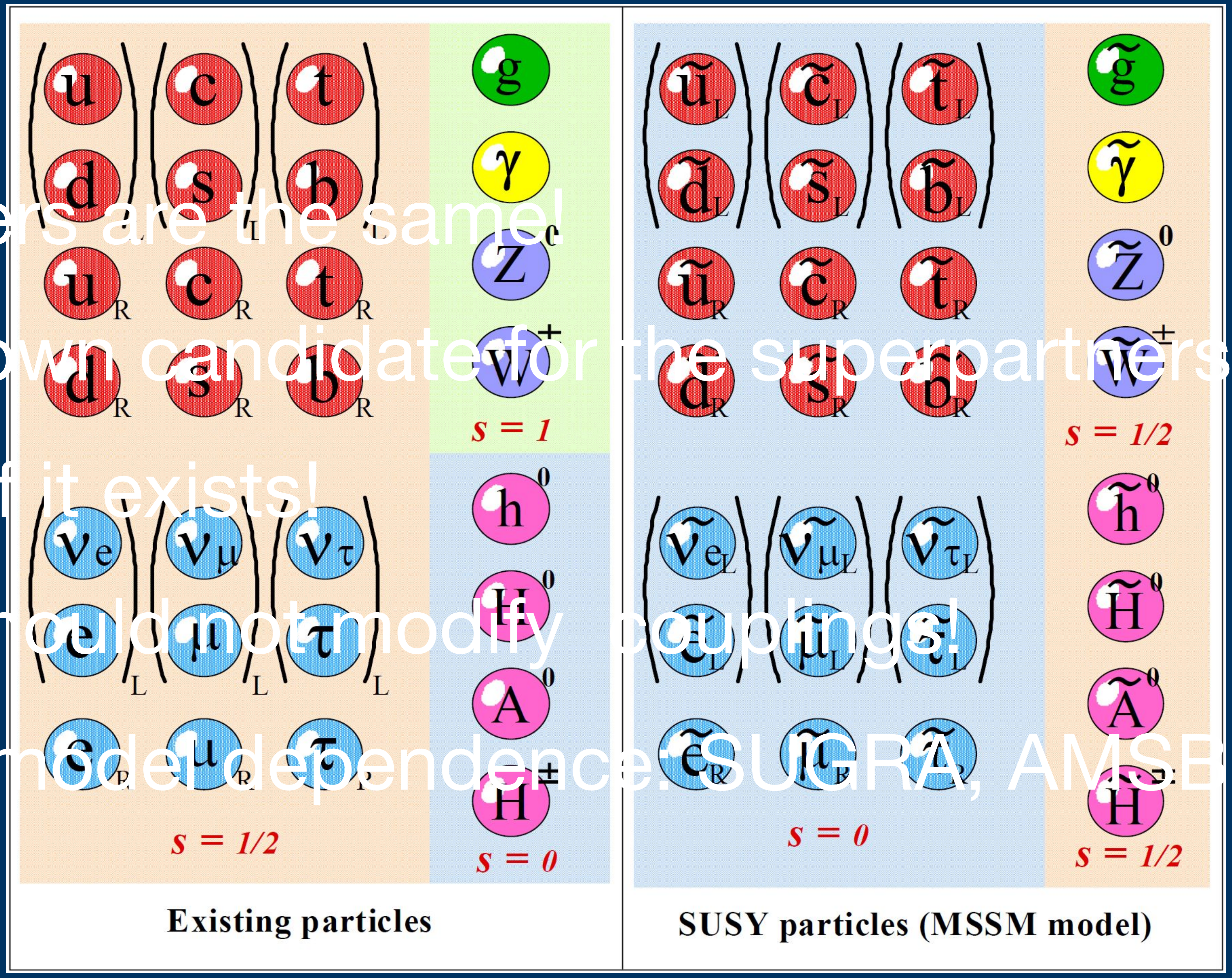


$$\Delta m_h \propto -c\Lambda^2$$

Supersymmetry

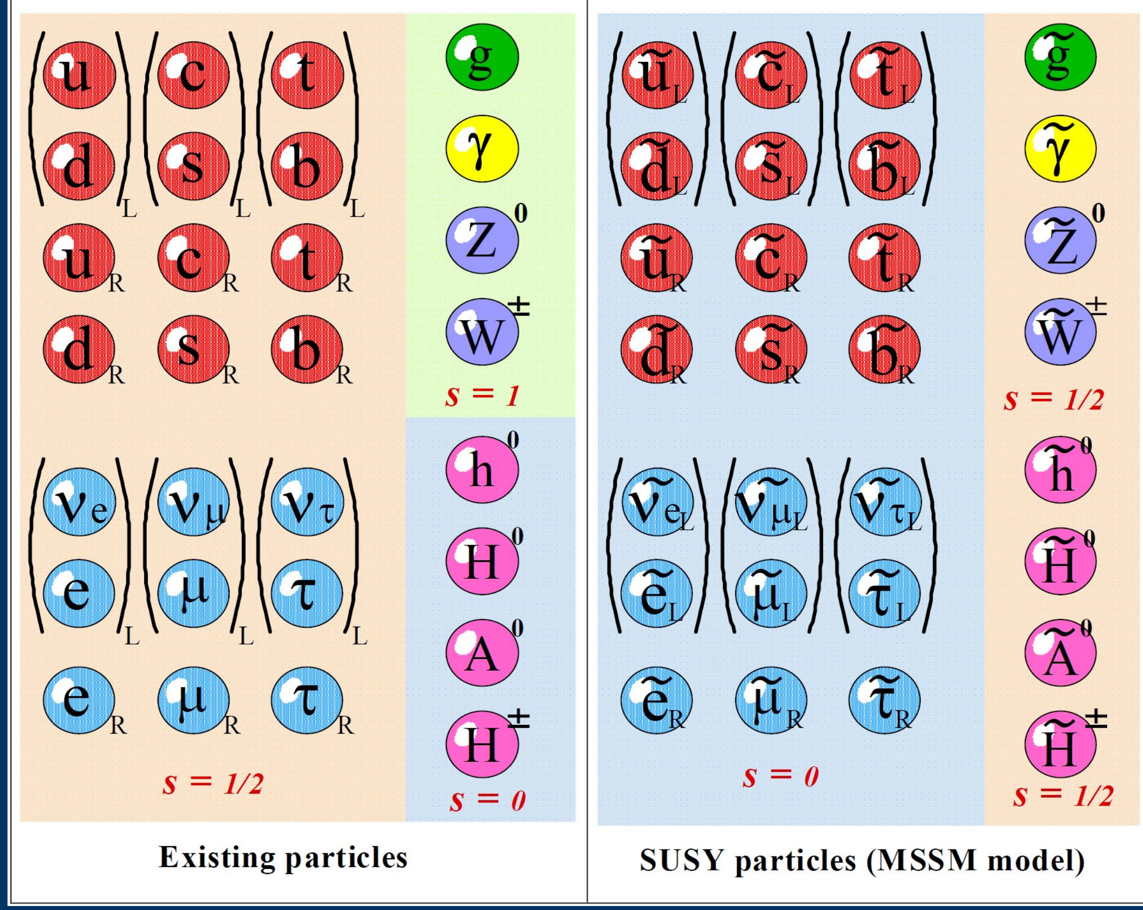


- SUSY: Q is a spin-$\frac{1}{2}$ generator
- $Q\,|\,\text{boson}\rangle \simeq |\,\text{fermion}\rangle$ and $Q\,|\,\text{fermion}\rangle \simeq |\,\text{boson}\rangle$
- SUSY “Doubles" the spectrum with superpartners with spin differing by $\frac{1}{2}$

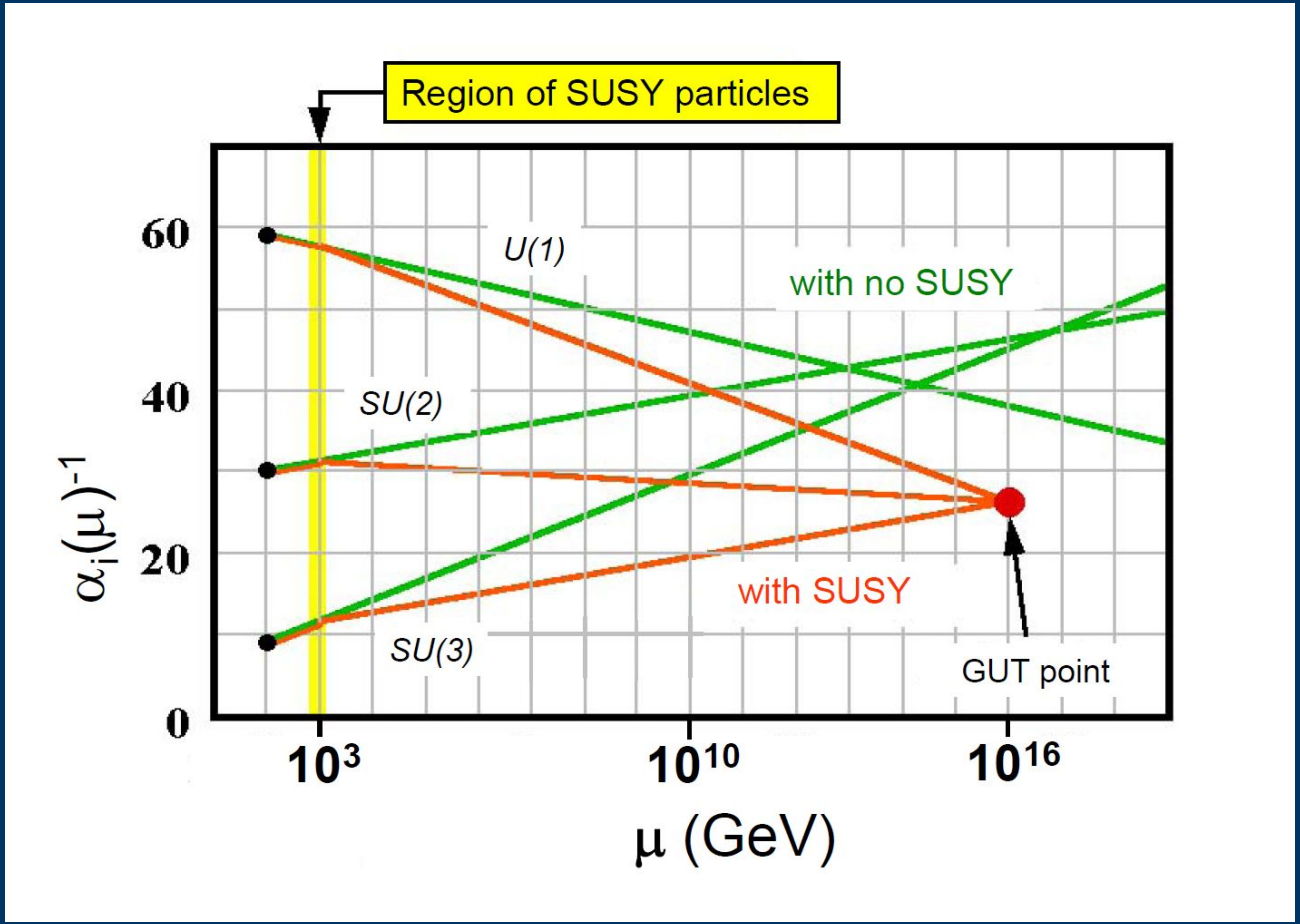


- Masses of the superpartners are the same!
- PROBLEM: there is no known candidate for the superpartners!
- SUSY is broken in nature if it exists!
- Constraint: the breaking should not modify couplings!
- SUSY breaking introduce model dependence: SUGRA, AMSB, etc

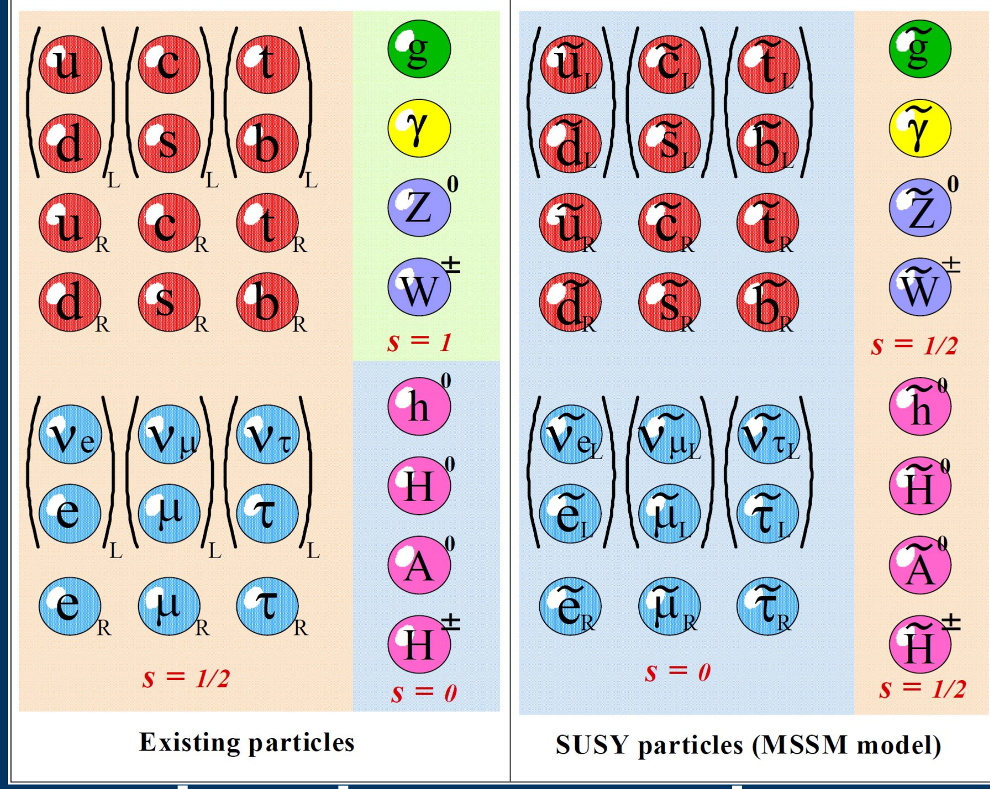
Supersymmetry



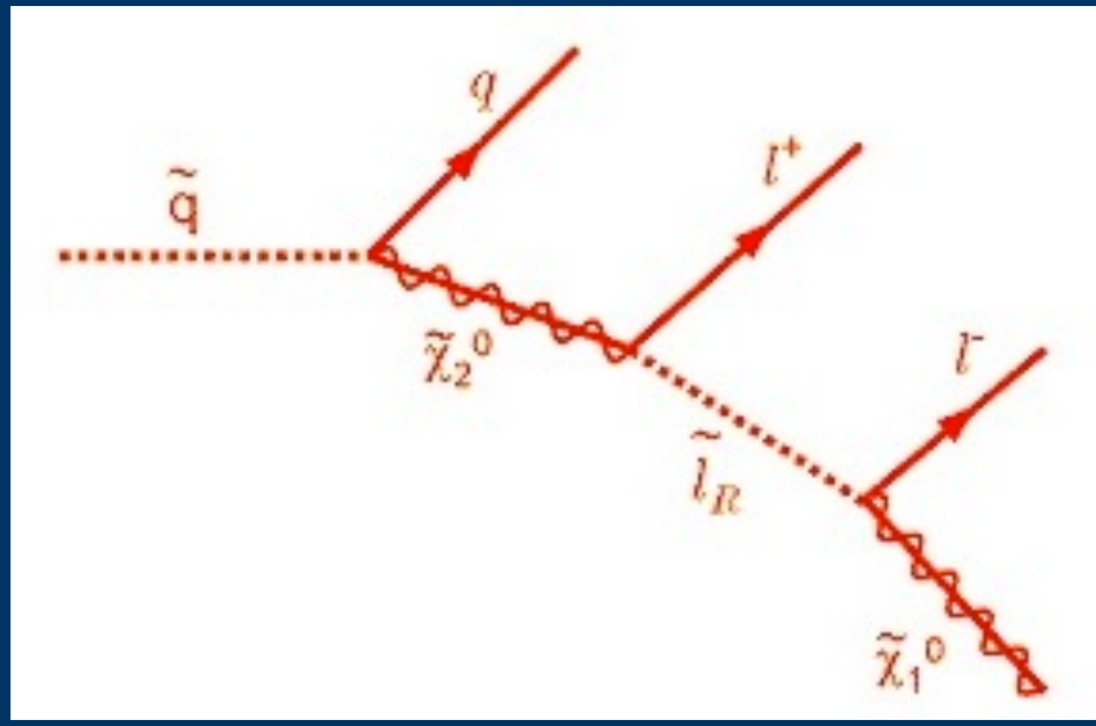
- It is possible to have grand unification: new contributions to RGE

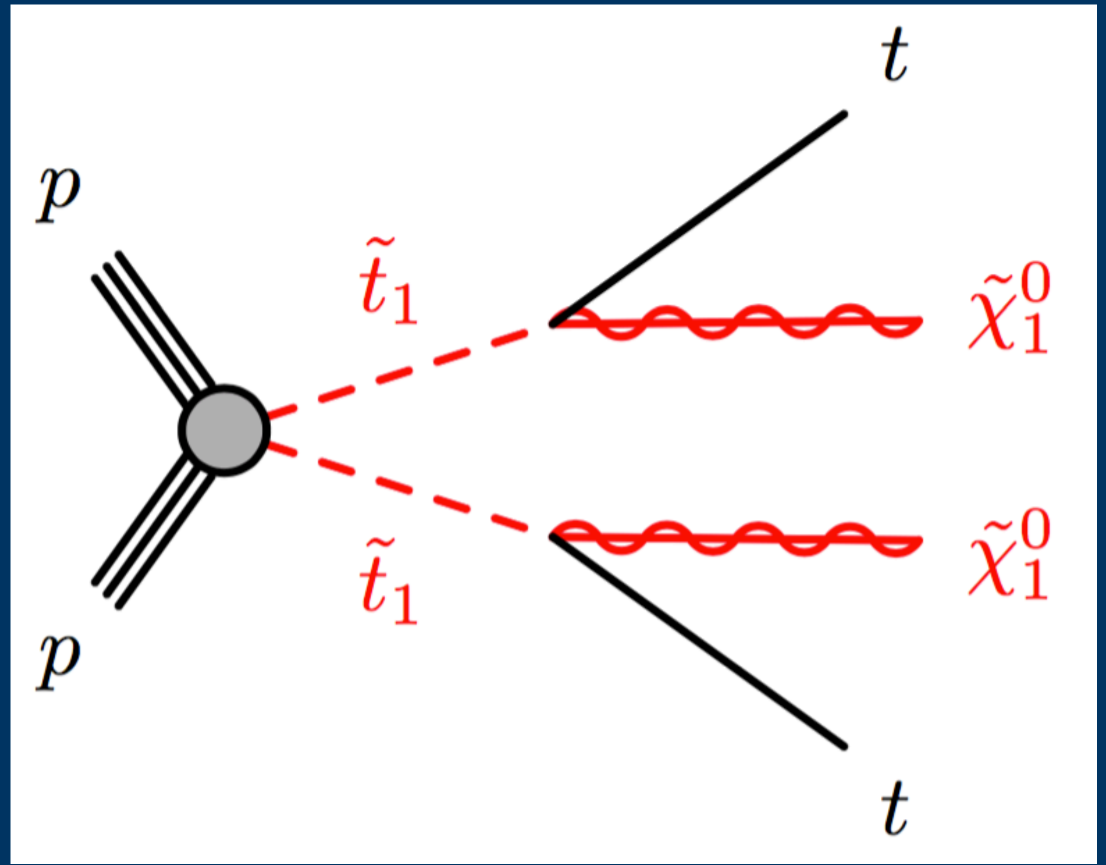


Supersymmetry: minimal supersymmetric SM (MSSM)



- EW symmetry breaking sector needs 2 doublets
- MSSM contains explicit SUSY breaking terms (hidden sector)
- Soft SUSY breaking preserving cancelations: gaugino and scalar masses + scalar interactions
- large number of parameters (178) $\Longrightarrow$ constraints + different scenarios
- sparticle spectrum is a characteristic of the model
- R-parity conservation: $R = (-1)^{3(B-L)+2S}$
- $\Longrightarrow$ the lightest SUSY particle (LSP) is stable
- $\Longrightarrow$ decay of SUSY particles terminates in the LSP
- $\Longrightarrow$ SUSY particles are pair produced
- $\Longrightarrow$ LSP is candidate to dark matter



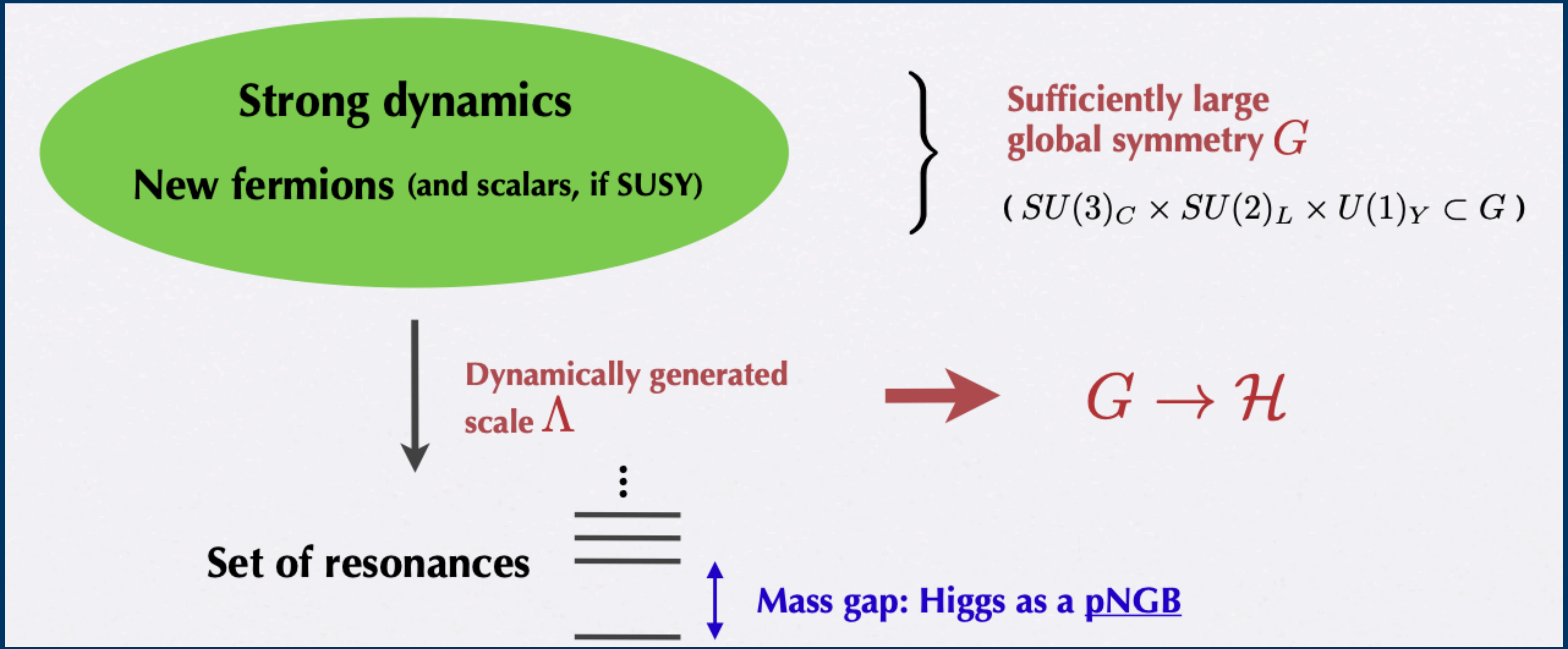


Composite Higgs Models

- Composite Higgs models: the Higgs is a bound state
- In QCD: $\langle \overline{q}^j_L q^k_R \rangle = \Lambda^3_{\mathrm{QCD}} \delta_{jk} \implies SU(2)_L \otimes SU(2)_R \to SU(2)_{L+R}$ breaks EW symmetry
- Technicolor models “imitate" QCD but the idea does not work!
- The hierarchy problem disappear is not sensitive to masses above the composites scale Λ
- The Higgs is a pseudo-Nambu-Goldstone boson (pNGB) [Georgi-Kaplan 80’s]
- Strongly interacting theory has a global symmetry G broken to H at scale Λ
- Key element: the symmetry G is only approximate $\implies$ pNGB

Composite Higgs Models

- Composite Higgs models: Higgs is a pNGB



- In the modern version $SU(2)_L \otimes U(1)_Y \subset \mathscr{H}$

Composite Higgs Models

- Composite Higgs models: there are many possibilities

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+2} + \bar{\mathbf{4}}_{-2} = 2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

minimal model

- SM interactions explicitly break G generating a potential $V(H)$
- Many details to be worked out: symmetry breaking, fermions, etc
- Signatures: Higgs couplings ($g_{hVV} = g_{hVV}^{\mathrm{SM}}\sqrt{1 - v^2/f^2}$) ; new fermions, …

Extra dimensions

- Extra dimensions ($D = 4 + d$) also address the hierarchy problem
- Warm-up: massless scalar in $d = 1$ and the extra dimension is a circle of radius R

$$S = \int dy\, d^4x\, \frac{1}{2} \left[(\partial_\mu \varphi)^2 - (\partial_5 \varphi)^2 \right]$$

$$\partial_\mu^2 \varphi - \partial_5^2 \varphi = 0$$

$$\varphi(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{+\infty} \varphi^{(n)}(x)\; e^{iny/R} \quad \text{with} \quad \varphi^{(n)\,*} = \varphi^{(-n)}$$

$$S = \int d^4x \sum_{n \geq 0} \left(\partial_\mu \varphi^{(n)\,\dagger} \partial^\mu \varphi^{(n)} - \frac{n^2}{R^2} \,|\, \varphi^{(n)} \,|^2 \right)$$

4D effective theory is a Kaluza-Klein (KK) tower of particles of mass n/R !

Extra dimensions

- Warm-up: gauge field in $d = 1$ and the extra dimension is a circle of radius R
- Start with the Fourier decomposition

$$S_{\text{gauge}} = -\frac{1}{4}\int dy\, d^4x\, F_{MN}F^{MN} \quad \text{with} \quad M, N = 0,1,2,3,5$$

$$A_M(x,y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{+\infty} A_M^{(n)}(x)\, e^{iny/R}$$

- After a gauge transformation: $A_\mu^{(n)} \to A_\mu^{(n)} - i\frac{n}{R}\partial_\mu A_5^{(n)}$ and $A_5^{(n)} \to 0$ for $n > 0$

$$S_{\text{gauge}} = \int d^4x \left[-\frac{1}{4}\,(F_{\mu\nu}^{(0)})^2 + \frac{1}{2}(\partial_\mu A_5^{(0)})^2 + \sum_{n\geq 1}\left(-\frac{1}{4}\, F_{\mu\nu}^{(-n)}F_{\mu\nu}^{(n)} + \frac{1}{2}\frac{n^2}{R^2}\, A_\mu^{(-n)}A_\mu^{(n)} \right) \right]$$

Extra dimensions

- Warm-up: gauge field in $d=1$ and the extra dimension is a circle of radius R

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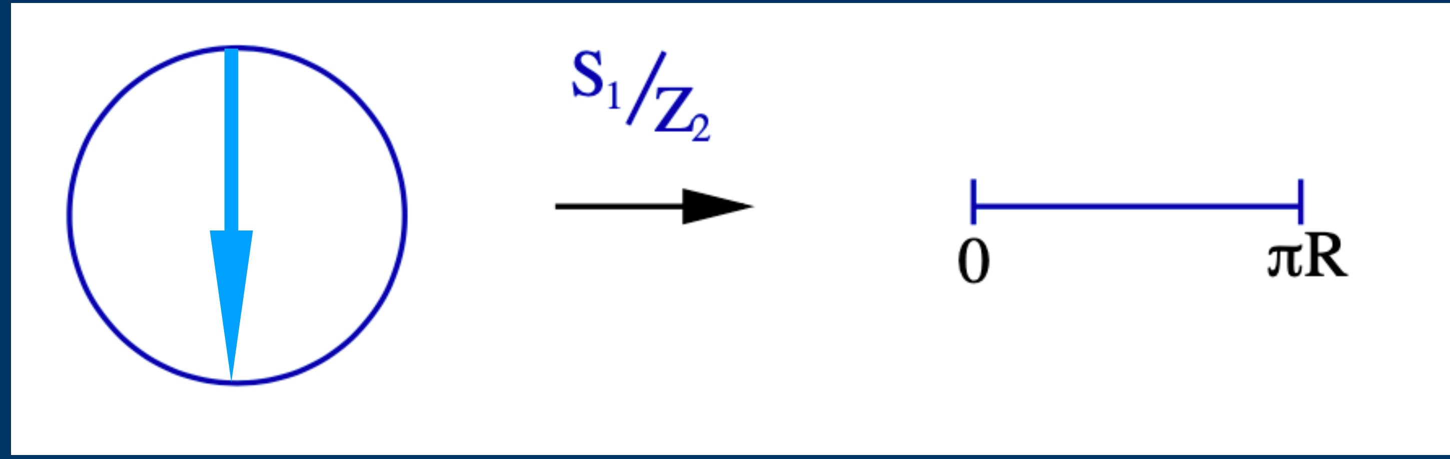
4D effective theory: 1 massless vector, 1 massless scalar and KK tower of vectors of mass n/R !

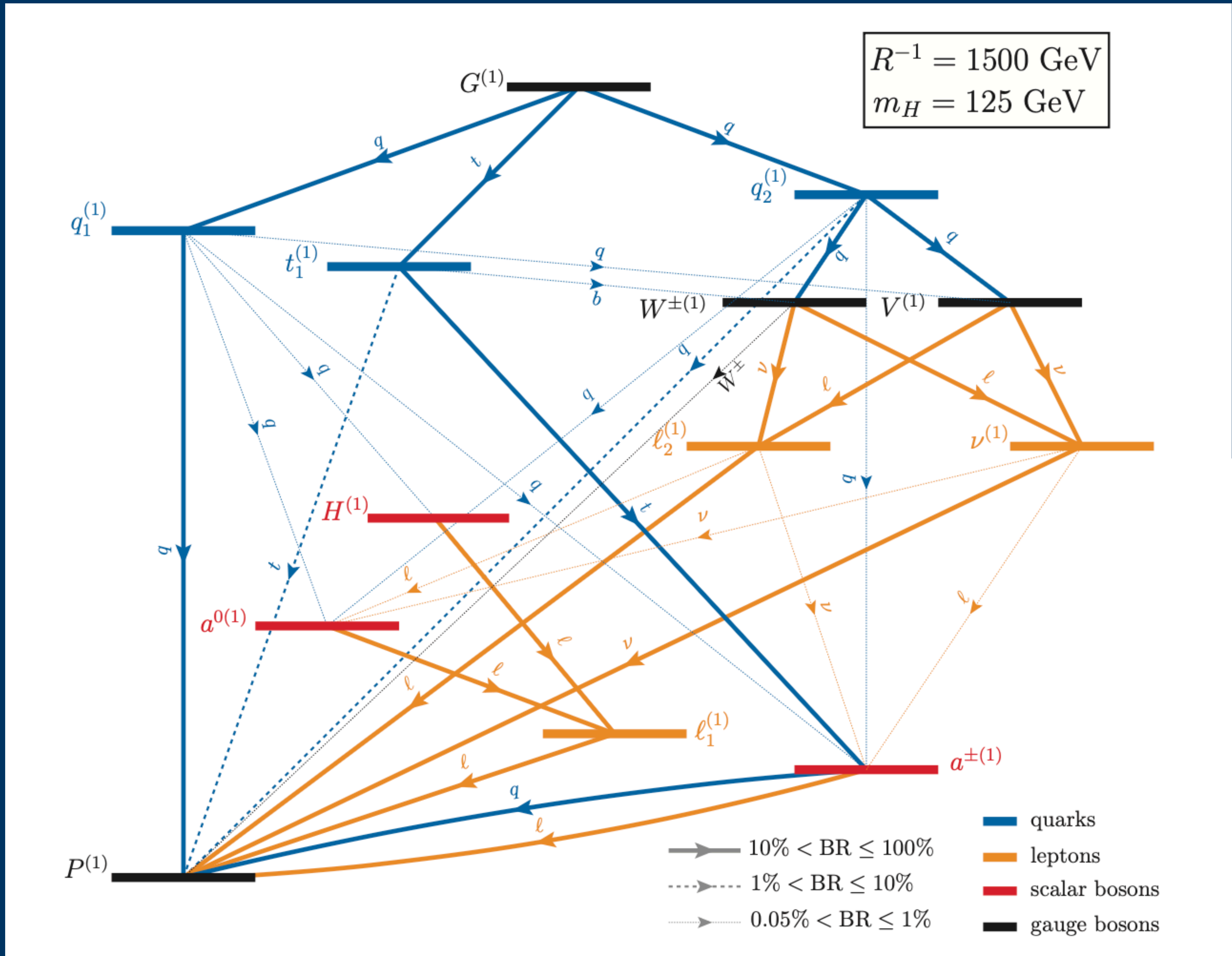
Extra dimensions

- Large extra dimensions: only gravity propagates in the extra dimensions
- Fundamental higher scale is M_*
- The effective 4D theory contains one massless graviton and its KK massive tower
- The Planck mass ($M_{\rm PL}$) is given by $M^2_{\rm PL} = M_*^{2+d}$ V where V is d volume
- This allow to lower the high scale, in the case, M_*
- For extra dimensions of radius R: $M^2_{\rm PL} = M_*^{2+d}\ R^d$
- M_* of the TeV order: $R = \dfrac{1}{M_*}\left(\dfrac{M_{\rm PL}}{M_*}\right)^{\frac{2}{d}}$ i.e. $R \leq \left(\dfrac{1}{\rm TeV}\right) 10^{\frac{32}{d}-17}$ cm
- To evade constraints: $d \geq 3$

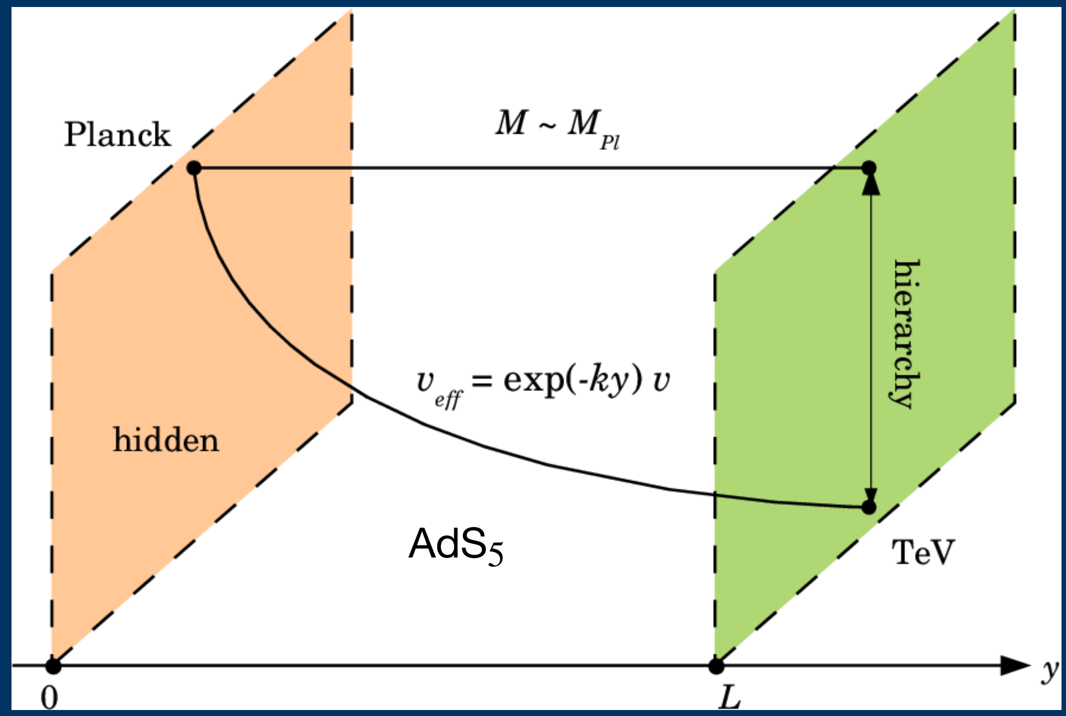
Extra dimensions



- Universal extra dimensions (UED): all SM particles propagate in the extra dimension
- To have 4D chiral fermions: S_1/Z_2 compactification identifying points
- At tree level $m_n^2 = m_0^2 + \frac{n^2}{R^2}$
- There is a KK parity: $(-1)^n$
- $n = 1$ UED "looks like" SUSY!
- Lightest KK particle (PKP) is stable
- Pair production

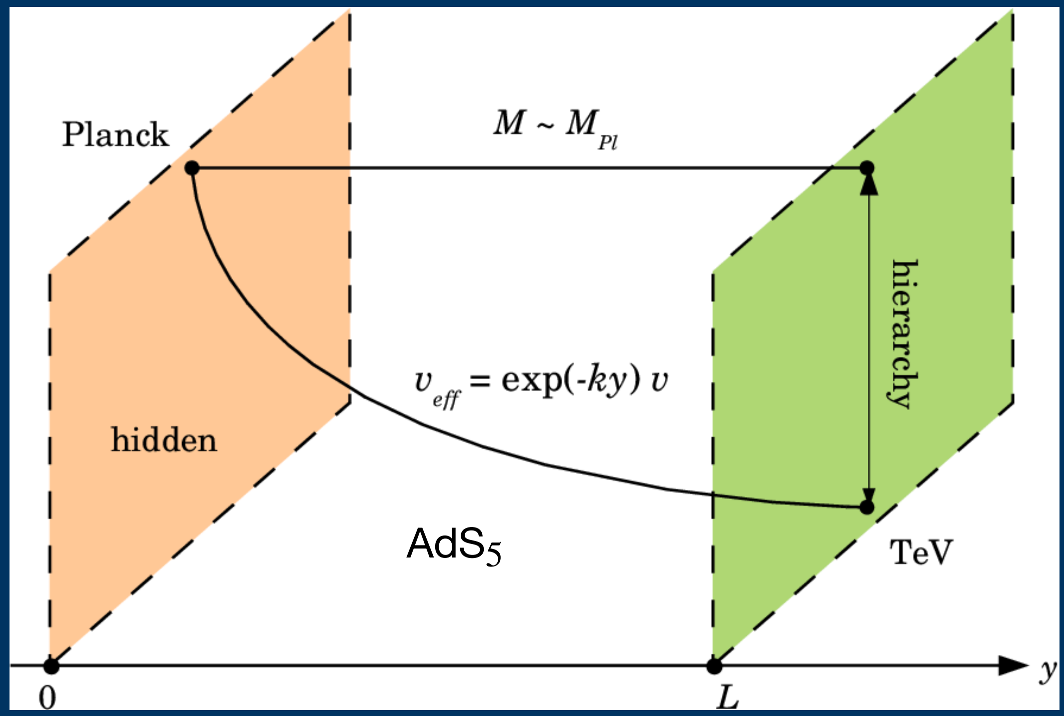


Extra dimensions



- Warped extra dimension: metric is nonfactorizable
- Randall-Sundrum $ds^2 = a(z)^2\ (\eta_{\mu\nu}dx^\mu dx^\nu - dz)$ with $a(z) = \dfrac{R}{z}$ and $R \leq z \leq R'$
- For a 5D complex scalar field: $S_5 = \displaystyle\int d^4x \int_R^{R'} dz\ \sqrt{g}\ \left[g^{MN}\partial_M\phi^*\partial_N\phi - m^2|\phi|^2\right]$
- Again, $\phi(x,z) = \dfrac{1}{\sqrt{R}} \displaystyle\sum_n \phi^{(n)}(x)\, f^{(n)}(z)$ where $\left[\partial_z^2 - \dfrac{3}{z}\partial_z + m_n^2 - \left(\dfrac{R}{z}m^2\right)\right] f^{(n)}(z) = 0$
- $f^{(n)}(z) = z^2\left[A_n J_\alpha(m_n z) + B_n Y_\alpha(m_n z)\right]$ with $\alpha = \sqrt{4 + m^2R^2}$
- the masses m_n are determined by boundary conditions (Dirichlet or Neumann)

Extra dimensions

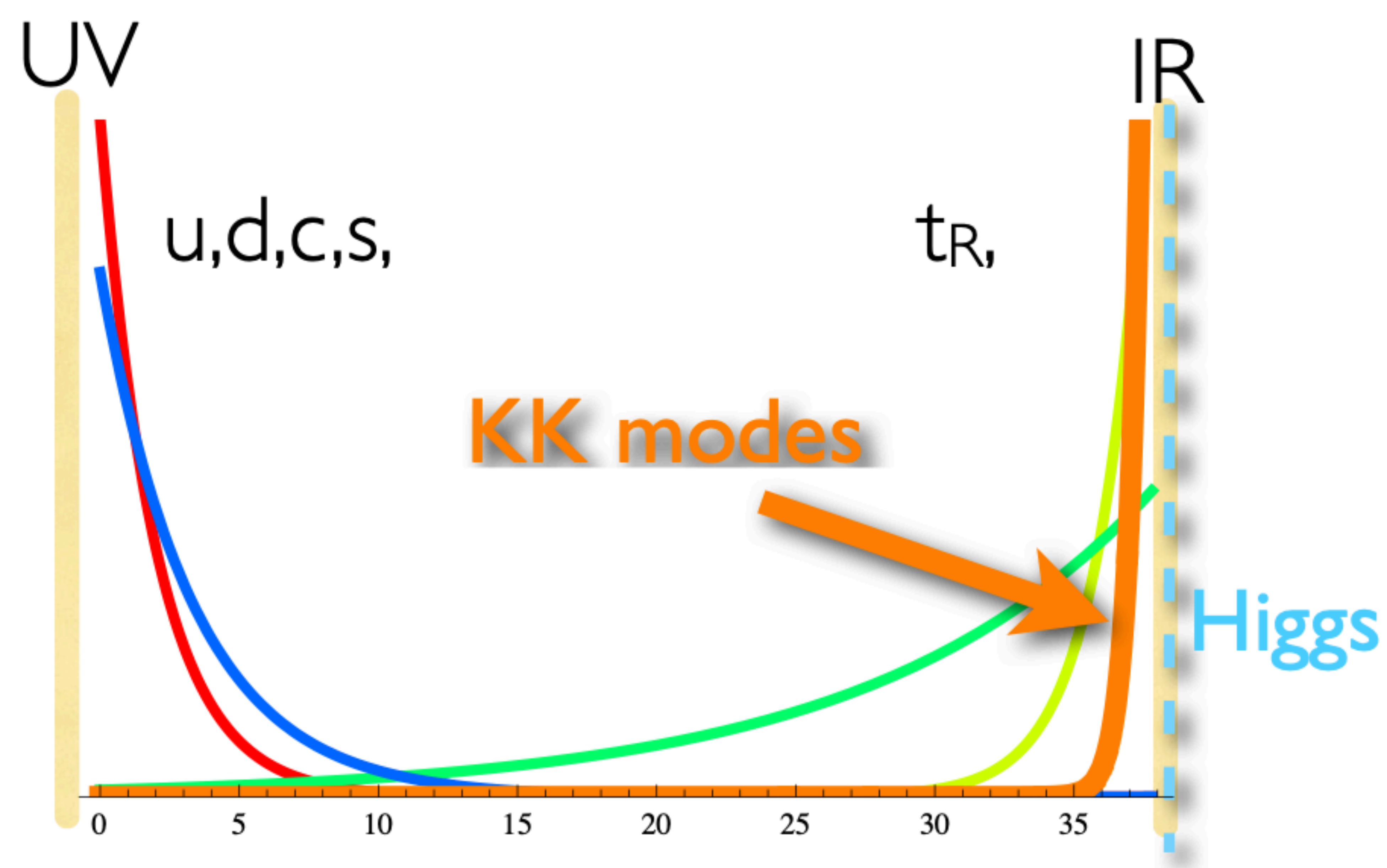


- Warped extra dimension: metric is nonfactorizable
- How this solve the hierarchy problem?
- Zero KK of the graviton:

$$S = M_*^3 \int_R^{R'} dz \left(\frac{R}{z}\right)^3 \int d^4x \sqrt{g_4} R_4 = \frac{M_*^3}{2} R \left(1 - \frac{R'^2}{R}\right) \int d^4x \sqrt{g_4} R_4$$

- Thus we have $M_{\rm PL}^2 = \dfrac{M_*^3}{2} R \left(1 - \dfrac{R'^2}{R^2}\right) \simeq M_*^2$ for $R = \dfrac{1}{M_*}$
- Well, does this solve the problem? Yes! If you localize the Higgs in the TeV brane!
- We can show that $v \simeq M_{\rm PL} \dfrac{R}{R'} \ll M_{\rm PL}$

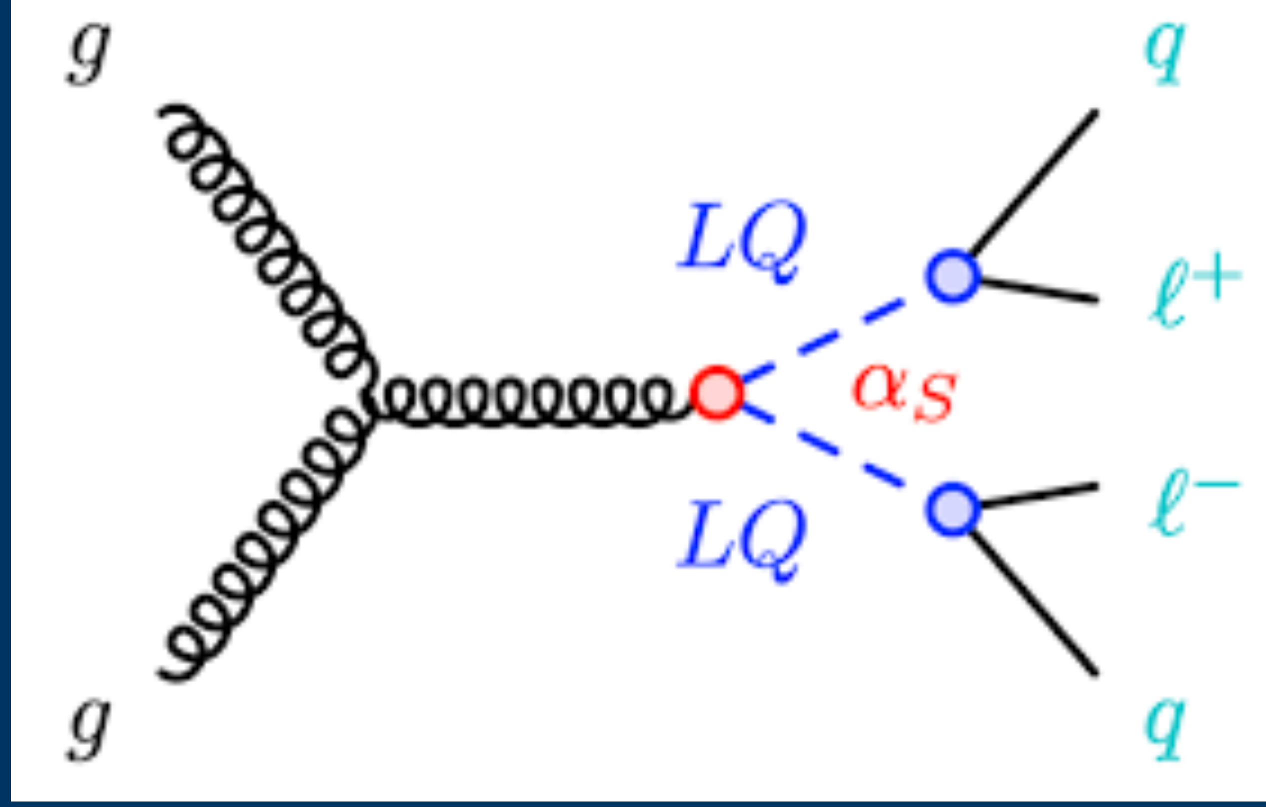
Extra dimensions



- Generic extra dimension model construction:

  1. Choose the geometry
  2. Choose the internal symmetry
  3. Choose where the fields propagate
  4. Obtain the KK decomposition of the fields and spectrum
  5. Integrate out the extra dimensions to get the 4D effective action
  6. Contrast with data and theoretical constraints; if the model fails go back to 1

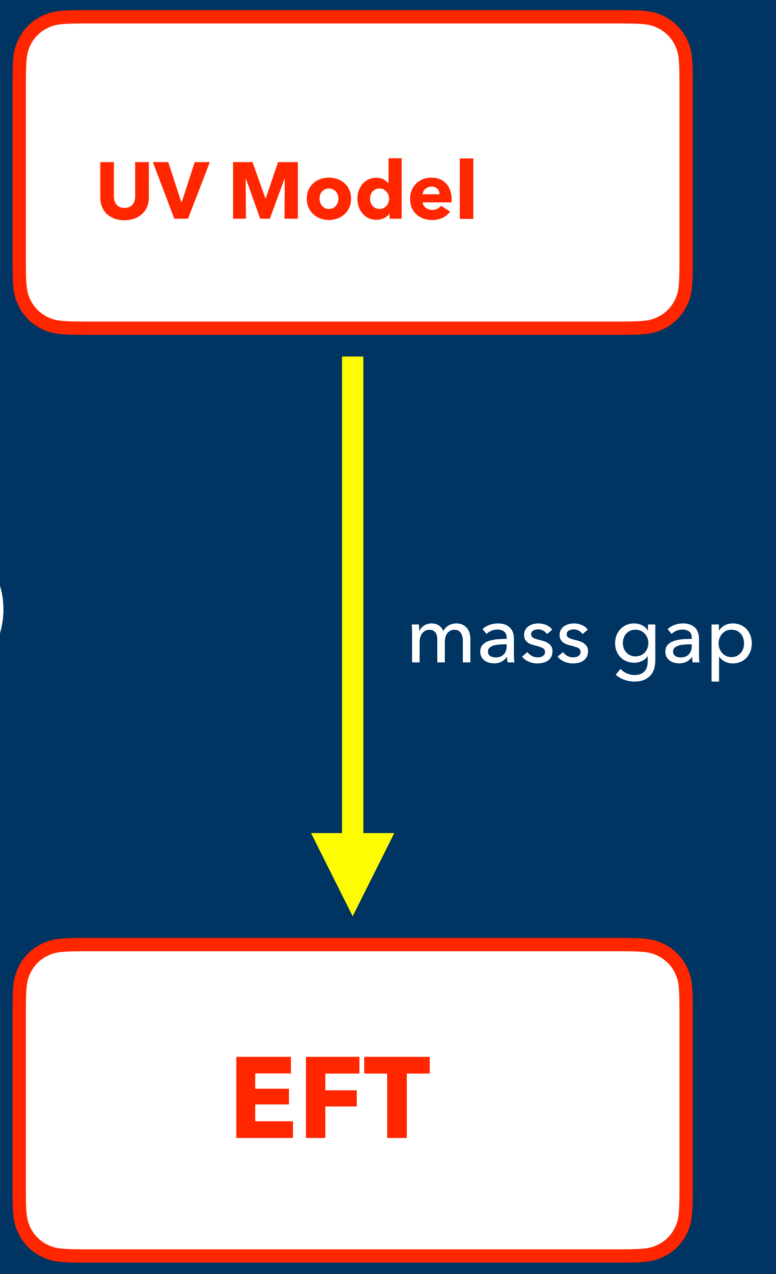
Leptoquarks



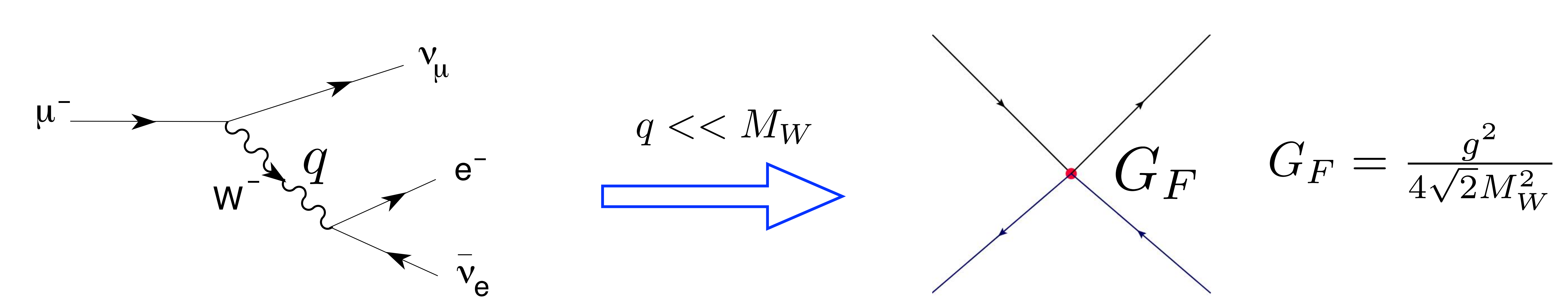
- Leptoquarks couple to lepton-quark pairs
- Motivation: explain anomalies in flavor physics
- $R^{(*)} = \dfrac{\text{Br}(B \to D^{(*)}\tau\nu)}{\text{Br}(B \to D^{(*)})\tau\nu}$ with $\ell = e, \mu$
- $R(D)_{\text{SM}} = 0.290 \pm 0.003$ while $R(D)_{\text{avg}} = 0.339 \pm 0.026$ $[1.87\sigma]$
- $R(D^*)_{\text{SM}} = 0.248 \pm 0.001$ while $R(D^*)_{\text{avg}} = 0.285 \pm 0.011$ $[3.35\sigma]$
- The interactions are described by renormalizable lagrangians
- $\mathscr{L} = -\, y_{kj}\ \bar{d}_R^k \tilde{R}_2^a (i\sigma^2)^{ab} L_L^{j,b} - x_{kj}^R\ \bar{u}_R^{C,k} e_R^j\ S_1 - x_{jk}^L\ \bar{Q}_L^{C,ka} (i\sigma^2)^{ab} (\vec{\sigma} \cdot \vec{S}_3)^{bc} L_L^{j,c} + \ldots$
- Anomalies can be accommodated as well as neutrino masses

EFFECTIVE FIELD THEORY

Effective field theory

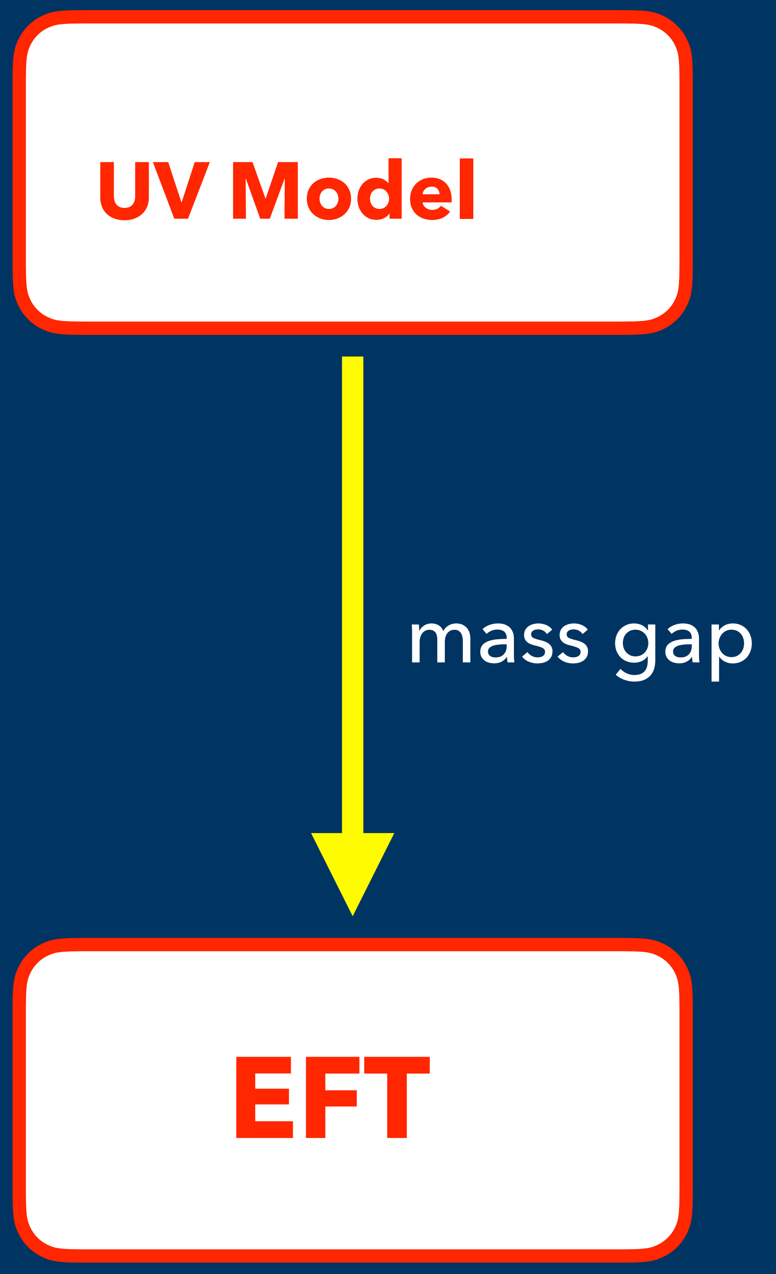


- Hypothesis: there is a mass between the EW (v) and BSM (Λ) energy scales
- We can parametrize low-energy BSM effects using an effective field theory (EFT)
- Example: the Fermi four-fermion interaction



- EFT is a consistent QFT
- Powerful calculation tool
- BSM: EFT allow us to perform model independent studies! For instance: Fermi interaction!

Effective field theory



- To construct a low-energy EFT we need to know:

    1. The low-energy particle content
    2. Symmetries and their transformation properties
    3. Expansion parameter

- Let's construct the SM effective field theory (SMEFT)
- Particle content: just the SM particles (Q_L , q_L , L_L , ℓ_R , ν_L , B_μ , W_μ^a , φ)
- Symmetry: $SU(2)_L \otimes U(1)_Y$
- Assuming that the Higgs belongs to a doublet $\Longrightarrow$ symmetry is linearly realized $M' = GM$
- Mass scale (Λ) of the UV physics

Effective field theory

- SMEFT expansion in powers of Λ

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{j\geq 5} \frac{f_{j,k}}{\Lambda^{j-4}} \mathscr{O}_j^{(k)}$$

- $\mathscr{O}_j^{(k)}$ has mass dimension j
- At dimension five: $c_{kn}\ L^k\tilde{\varphi}\ L^n\tilde{\varphi}$ where c_{kn} is a 3×3 matrix in flavor space $\implies m_\nu$
- Important fact: operators related by the EOM have the same S matrix elements

$$(\partial_\mu B^{\mu\nu})^2 \simeq c_1(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)^2 + \sum_\psi c_\psi (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\ \bar{\psi}\gamma^\mu\psi + \sum_{\psi,\psi'} c_{\psi,\psi'}(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}'\gamma^\mu\psi')$$

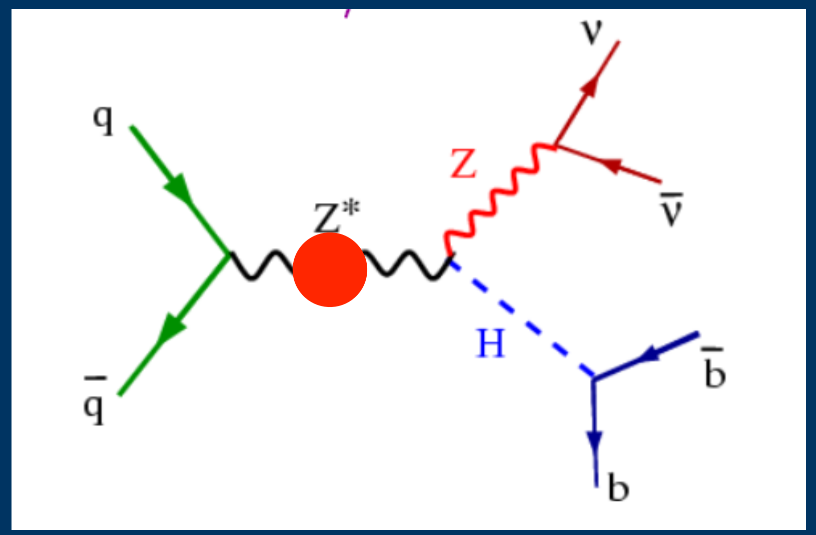
Effective field theory

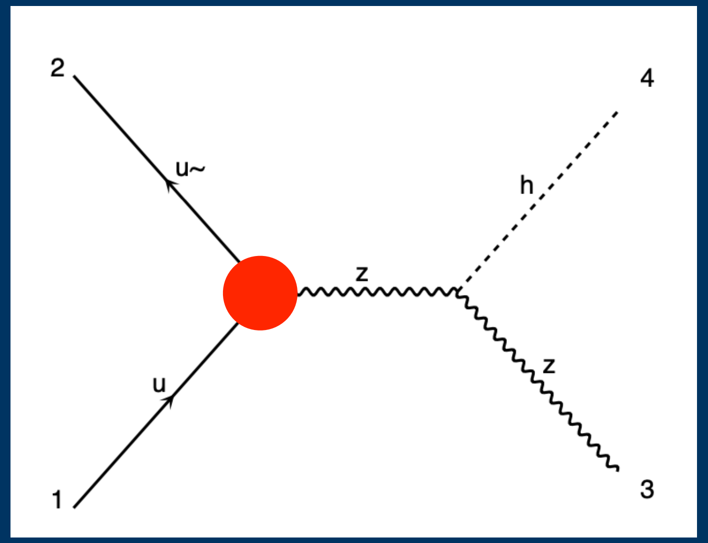
- SMEFT expansion in powers of Λ

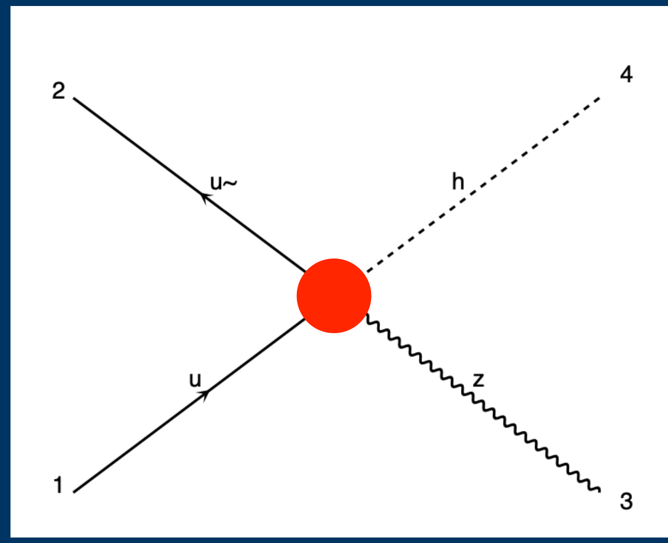
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{j\geq 5} \frac{f_{j,k}}{\Lambda^{j-4}} \mathscr{O}_j^{(k)}$$

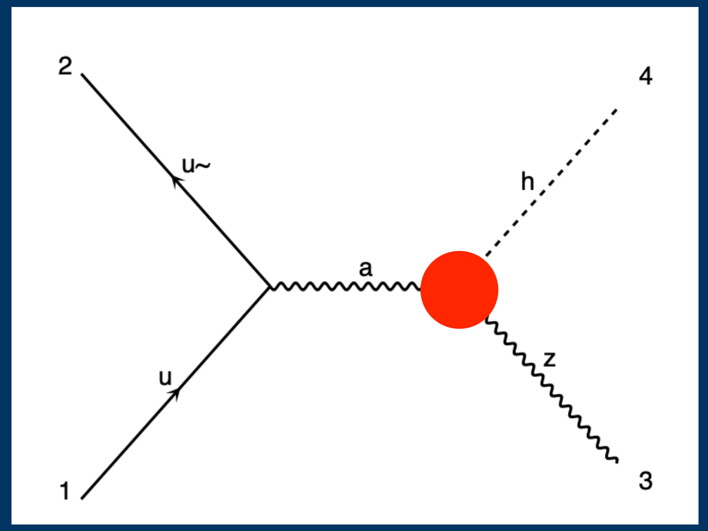
- Important fact: operators related by the EOM have the same S matrix elements

$$(\partial_\mu B^{\mu\nu})^2 \simeq c_1(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)^2 + \sum_\psi c_\psi (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\, \bar\psi\gamma^\mu\psi + \sum_{\psi,\psi'} c_{\psi,\psi'} (\bar\psi\gamma^\mu\psi)(\bar\psi'\gamma^\mu\psi')$$









- In actual calculations we need a minimal number of independent operators, i.e. a basis!

Effective field theory

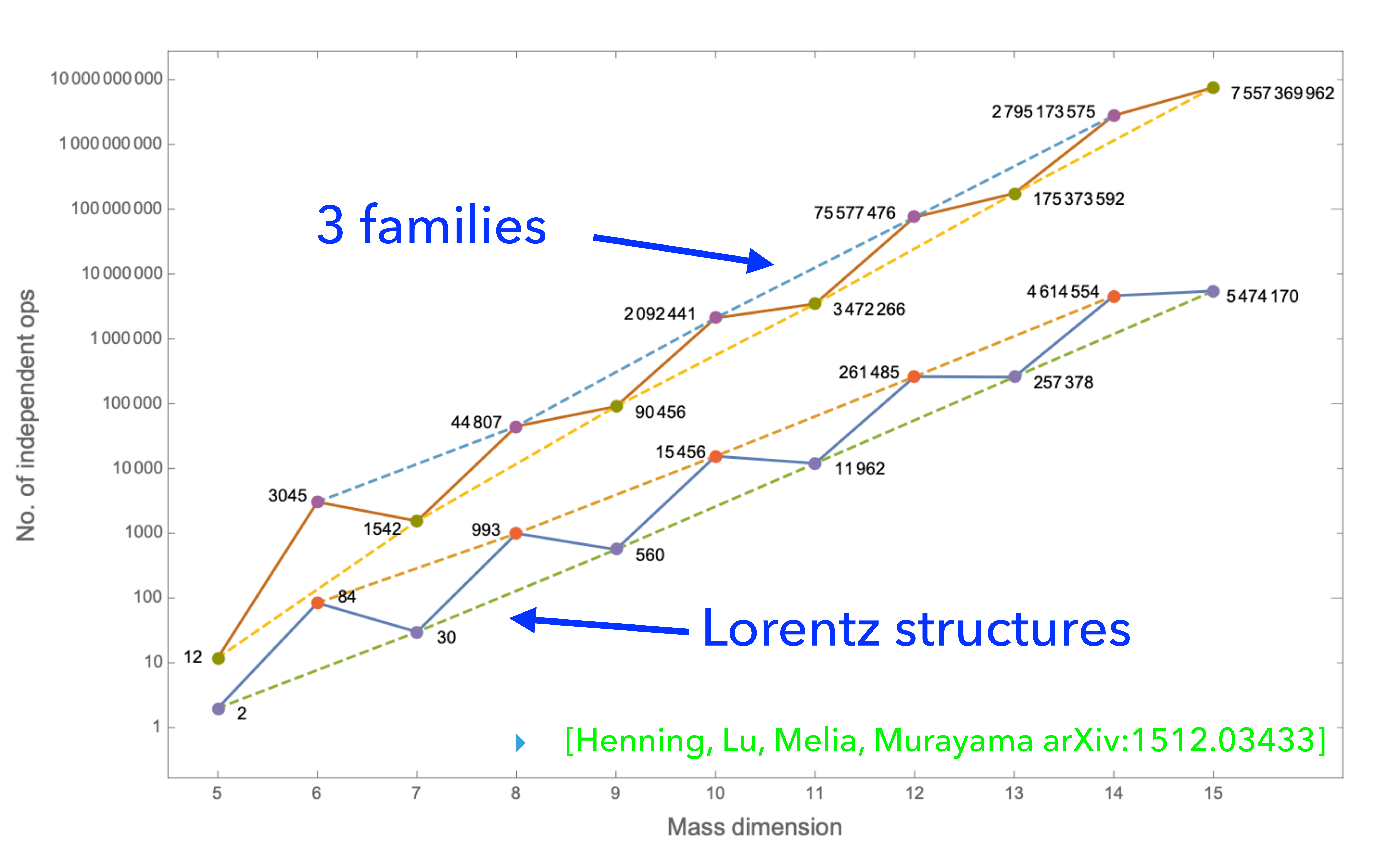
- At dimension six, there are 59 structures not taking flavor into account
- A popular basis is the Warsaw basis [Grzadkowski et al. arXiv:1008.4884]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r) \varepsilon_{jk} (\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \varepsilon_{jk} (\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r) \varepsilon_{jk} (\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} \left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		

Effective field theory

- At dimension
- Taking flavor
- Without any f
- The number o
- Using Hilbert



Effective field theory

- Linear realization of the symmetry leads to correlations:

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \ ,$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \quad , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right)$$

	ZWW	γWW	$H\gamma\gamma$	HZZ	$HZ\gamma$	HWW
$\mathcal{O}_{WWW}$	X	X				
$\mathcal{O}_W$	X	X		X	X	X
$\mathcal{O}_B$	X	X		X	X	
$\mathcal{O}_{BW}$	X	X	X	X	X	X
$\mathcal{O}_{WW}$			X	X	X	X
$\mathcal{O}_{BB}$			X	X	X	
$\mathcal{O}_{\Phi,1}$	X			X		X
$\mathcal{O}_{\Phi,2}$				X		X

relacionados pela invariância de gauge

Remarks

Remarks

- Despite its successes, the SM is not the final theory
- The SM does not answer all our questions!
- There is no smoking gun of New Physics $\Longrightarrow$ there is a vast model territory to be explored
- We have good reasons to keep looking for clues and possibilities.